

Whole-Body-Vibration Training Increases Knee-Extension Strength and Speed of Movement in Older Women

Machteld Roelants, MS,* Christophe Delecluse, PhD,* and Sabine M. Verschueren, PhD†

OBJECTIVES: To investigate the effects of 24 weeks of whole-body-vibration (WBV) training on knee-extension strength and speed of movement and on counter-movement jump performance in older women.

DESIGN: A randomized, controlled trial.

SETTING: Exercise Physiology and Biomechanics Laboratory, Leuven, Belgium

PARTICIPANTS: Eighty-nine postmenopausal women, off hormone replacement therapy, aged 58 to 74, were randomly assigned to a WBV group (n = 30), a resistance-training group (RES, n = 30), or a control group (n = 29).

INTERVENTION: The WBV group and the RES group trained three times a week for 24 weeks. The WBV group performed unloaded static and dynamic knee-extensor exercises on a vibration platform, which provokes reflexive muscle activity. The RES group trained knee-extensors by performing dynamic leg-press and leg-extension exercises increasing from low (20 repetitions maximum (RM)) to high (8RM) resistance. The control group did not participate in any training.

MEASUREMENTS: Pre-, mid- (12 weeks), and post- (24 weeks) isometric strength and dynamic strength of knee extensors were measured using a motor-driven dynamometer. Speed of movement of knee extension was assessed using an external resistance equivalent to 1%, 20%, 40%, and 60% of isometric maximum. Counter-movement jump performance was determined using a contact mat.

RESULTS: Isometric and dynamic knee extensor strength increased significantly ($P < .001$) in the WBV group (mean \pm standard error $15.0 \pm 2.1\%$ and $16.1 \pm 3.1\%$, respectively) and the RES group ($18.4 \pm 2.8\%$ and $13.9 \pm 2.7\%$, respectively) after 24 weeks of training, with the training effects not significantly different between the groups ($P = .558$). Speed of movement of knee extension significantly increased at low resistance (1% or 20% of isometric maximum) in the WBV group only ($7.4 \pm 1.8\%$ and $6.3 \pm 2.0\%$, respectively) after 24 weeks of training, with

no significant differences in training effect between the WBV and the RES groups ($P = .391$; $P = .142$). Counter-movement jump height enhanced significantly ($P < .001$) in the WBV group ($19.4 \pm 2.8\%$) and the RES group ($12.9 \pm 2.9\%$) after 24 weeks of training. Most of the gain in knee-extension strength and speed of movement and in counter-movement jump performance had been realized after 12 weeks of training.

CONCLUSION: WBV is a suitable training method and is as efficient as conventional RES training to improve knee-extension strength and speed of movement and counter-movement jump performance in older women. As previously shown in young women, it is suggested that the strength gain in older women is mainly due to the vibration stimulus and not only to the unloaded exercises performed on the WBV platform. *J Am Geriatr Soc* 52:901–908, 2004.

Key words: whole-body-vibration training; muscle strength; resistance training; speed of movement; counter-movement jump

Muscle strength and, particularly, peak muscle power have a strong influence on how older adults function in activities of daily living such as walking, climbing stairs, and rising from a chair.^{1–3} In addition, muscle weakness and the ability of lower extremity muscles to develop force rapidly have been found to be the most common risk factors for falls and hip fractures in older adults.^{4,5} Therefore, the prevention of age-related strength loss and muscle atrophy is a public health issue.^{6–9}

Reduction in muscle mass with a preferential loss of type II fibers¹⁰ has been associated with an age-related decrease in physical activity resulting in reduced loading of the musculoskeletal system.¹¹ Moreover, some studies have reported that decreases in serum sex hormones are involved in a reduction of muscle mass,^{12,13} whereas other studies have not supported these findings.¹⁴ Fortunately, it has been proven that resistance and explosive strength training programs can alleviate deterioration of the muscular system with aging.^{3,15–18} Recently, whole-body-vibration (WBV) training has been promoted as an efficient alternative for resistance training. In WBV training, the subject stands or

From the *Exercise Physiology and Biomechanics Laboratory and †Laboratory of Motor Control, Faculty of Physical Education and Physiotherapy, Department of Kinesiology, Katholieke Universiteit Leuven, Leuven, Belgium.

Address correspondence to Christophe Delecluse, PhD, Faculty of Physical Education and Physiotherapy, Tervuursevest 101, 3001 Leuven, Belgium. E-mail: christophe.delecluse@flok.kuleuven.ac.be

moves (unloaded) on a platform that generates vertical sinusoidal vibration at a frequency between 25 Hz and 40 Hz, with amplitude varying between 2.0 mm and 10.5 mm.^{19–22} These mechanical stimuli are transmitted to the body where they in turn stimulate sensory receptors, most likely muscle spindles.^{23–25} The activation of the sensory receptors results in the activation of the alpha-motoneurons and initiates muscle contractions comparable to the tonic vibration reflex.^{23–25}

Immediately after one WBV session, positive effects on muscle performance and on vertical jump performance were recorded in some but not all studies.^{26–28} Next to the analysis of these acute effects of WBV, a limited number of studies analyzed the effects of WBV over a longer period (10 days to 4 months).^{19,20,22} All of these studies demonstrated the beneficial effect of WBV on muscle strength in young adults. One study²⁰ showed that 12 weeks of WBV training (35–40 Hz; 2.28–5.09 gravitation field (g)) increased isometric and dynamic knee-extensor strength in previously untrained young women 16.6% and 9.0%, respectively. That study included a placebo group that performed an identical exercise program on a “placebo” vibration platform. The subjects of the placebo group were convinced that they were performing a real WBV program because they could hear the motor, and they experienced tingling on the soles of their feet, but the acceleration on the platform was only 0.4 g. It was shown that strength increases after WBV training were clearly associated with the real vibration stimulus (2.28–5.09 g) and were not attributable to the unloaded exercise program performed on the platform. The magnitude of the strength gain after WBV was comparable with the increase in muscle strength after an equal number of resistance training sessions.²⁰

Therefore, it was suggested that WBV had a great potential in a therapeutic context,²⁸ where it may enhance muscular performance in patients and older adults who are not attracted to or are not able to perform standard exercise programs. Older adults are more prone to overload the musculoskeletal and cardiovascular system because of the diminished ability of the aging body to adapt to high levels of loading.²⁹ Even if performed to exhaustion, the increases in heart rate, blood pressure, and oxygen uptake during WBV are mild, so the cardiovascular risks of WBV in older adults are negligible.²¹

A pilot study in older women (data not shown) demonstrated that the muscle activity (electromyography recordings) of the lower extremities in a squat position is clearly higher with vibration (35 Hz) than without vibration. Some studies have suggested that the tonic vibration reflex facilitates the activation of high-threshold motor units.^{21,30} This may have an effect on recruitment patterns and on the mean area of fast-twitch fibers, which play an important role in muscle strength and power in older adults.¹⁶ In addition, a study³¹ suggested that the tonic vibration reflex induces a facilitation of the reflex action on the motoneuron pool, which might positively influence strength in muscle contractions including a stretch shortening cycle in daily activities. However, reports of the effects of WBV in older adults are lacking. Therefore it was the objective of this study to analyze the effects of 24 weeks of WBV training on strength and speed of movement of the knee extensors and on counter-movement jump perfor-

mance in older women. The potential of WBV to induce performance-enhancing effects is compared with the changes that conventional resistance training in older women can generate.

METHODS

Subjects

Postmenopausal women not taking hormone replacement therapy and not engaged in regular organized physical activities or strength training were recruited to participate in the study. All candidates underwent an extensive medical examination and performed a graded ergometer test to maximum exercise capacity. Subjects were excluded if they had metabolic or neuromuscular diseases, osteoporosis, osteoarthritis, orthopedic injuries, or two or more risk factors for coronary artery disease. Eighty-nine subjects met all inclusion criteria and were allowed to participate in this study. The modified Baecke Questionnaire for Elderly³² was used to quantify the amount and intensity of daily physical activity to control for baseline differences in physical activity between groups. All subjects gave written informed consent to participate. The university's human ethics committee approved this study according to the Helsinki Declaration.

Power analysis revealed that a sample size of 22 subjects in each group was necessary to achieve a power of 0.80 with $\alpha = 0.05$. In anticipation of inevitable dropout, it was decided to select 30 subjects in the training groups. All subjects were randomly assigned to a control group ($n = 29$) or to one of the training groups: the WBV training ($n = 30$) or the resistance training (RES, $n = 30$). The training programs consisted of 72 training sessions over a 24-week period. Training frequency was three times a week, with at least 1 day of rest between sessions. The control group did not participate in any training program, and these subjects were instructed not to change their lifestyle.

Training Programs

WBV Group

The WBV training performed a total-body-training program consisting of unloaded static and dynamic exercises on the vibration platform (Power Plate, Badhoevendorp, The Netherlands). The lower body exercises included high squat (knee angle between 120° and 130°) and deep squat (knee angle 90°), wide-stance squat, and lunge. Training volume and training intensity were low at the beginning but progressed slowly according to the overload principle. The training volume was increased systematically over the 24-week training period by increasing the duration of one vibration session, the number of series of one exercise, or the number of different exercises. The training intensity was increased by shortening the rest periods or increasing the amplitude (2.5–5.0 mm) or the frequency (35 Hz–40 Hz) of the vibration (Table 1). In addition, training intensity was increased by changing the execution form of the exercises from predominantly two-legged to one-legged exercises. The duration of the WBV programs was a maximum of 30 minutes including warming up and cooling down.

Table 1. Training Volume and Training Intensity of the Whole-Body-Vibration Training Program

Parameter	Start	Week 12	Week 24
Volume			
Total duration of vibration in one session, minutes	3	20	30
Series of one exercise, n	1	3	3
Different knee-extensor exercises, n	2	6	9
Longest duration of vibration loading without rest, seconds	30	60	60
Intensity			
Rest period between exercises, seconds	60	5	5
Vibration amplitude, mm	2,5	5	5
Vibration frequency, Hz	35	40	40

Note: The status of each variable is described at the start of the training, at the end of the 12-week training, and at the end of 24-week training.

The acceleration of the vibration platform was recorded using an accelerometer (MTN 1800, Monitran, Bucks, UK) at low amplitude 2.28 g and 2.71 g at 35 Hz and 40 Hz, respectively, and at high amplitude 3.91 g and 5.09 g at 35 Hz and 40 Hz, respectively (g is the earth's gravitational field of 9.81 m/s²). During all WBV training sessions, subjects wore the same athletic shoes to standardize the damping of the vibration due to the footwear. The subjects were asked to report negative side effects or adverse reactions in their training diary.

RES Group

The magnitude of the effect of a commonly used WBV training program on muscle performance was compared with the changes after a conventional RES training program that is considered to be a standard method of increasing strength in older adults.³³ The RES group trained in the university fitness center. They started with a standardized warm-up consisting of 20 minutes cardiovascular exercises. The intensity was automatically heart-rate controlled (Technogym System, Rotterdam, The Netherlands). Thereafter, they performed a total body RES training program including leg extension and leg press (Technogym) to train the lower body. Because the WBV program used in this study was slowly progressive in nature, the RES training program was designed in the same way, starting at a low threshold of two sets of 20-repetition maximum (RM) in the first 2 weeks. The next 12 weeks of the RES training program was designed according to the guidelines of the American College of Sports Medicine for individuals aged 60 and older, with a training intensity of 10RM to 15RM, (the greatest weight that a participant could lift for 10–15 repetitions).³³ During these 12 weeks, the amount of weight lifted was systematically increased from a weight permitting two sets of 15RM, to two sets of 12RM, to two sets of 10RM. In the last 10 weeks, training volume and training intensity varied between three sets of 12RM and one set of 8RM.

During the first two training sessions, a health and fitness instructor individually assisted subjects to determine the 20RM load. In this group of older adults, the use of RM or the exact resistance that allows only a specific number of repetitions to be performed is the easiest and safest method to determine training workload. Subjects were observed and instructed to increase the workload in the following session or even in the following set if they felt capable of

performing more than the prescribed number of repetitions. In this way, leg extension and leg press exercises were executed systematically to fatigue failure with the objective of performing the prescribed number of repetitions. This procedure ensured a systematic increase of the training load over the 24-week training period. The RES program lasted about 1 hour. Certified (American College of Sports Medicine (ACSM)) health and fitness instructors closely supervised all training sessions of the WBV and RES groups. The trainer-to-subject ratio was one to three.

Outcome Measures

Strength Testing

The muscle characteristics of the knee extensors were evaluated at the start of the study (pretest), after 12 weeks of training (mid-test), and after 24 weeks of training (posttest). The same person conducted all of these measurements. Mid- and posttests were performed at least 72 hours after the last training session to avoid any acute effect of training sessions on test results. All subjects participated in a standardized warm-up and test protocol on a motor-driven dynamometer (REV9000, Technogym). During the warm-up the subjects performed the different types of contractions to experience all test conditions before testing.

Dynamometry

The knee-extension isometric strength, dynamic strength, and speed of movement tests were performed unilaterally on the right side, in a seated position on a backward-inclined (15°) chair. The upper leg, the hips, and the shoulders were stabilized with safety belts. The rotational axis of the dynamometer was aligned with the transverse knee-joint axis and connected to the distal end of the tibia using a length-adjustable rigid lever arm. The three-dimensional positions of the rotational axis, the position of the chair, and the length of the lever arm were identical in pre-, mid- and posttest.

Maximal Strength

Isometric strength: The subjects performed a maximal voluntary isometric contraction of the knee extensors twice. The knee-joint angle was 130°. The isometric contractions lasted 3 seconds each and were separated by a 2-minute rest interval. The highest torque (Nm) was recorded as isometric strength performance. The intraclass correlation coefficient

(ICC) for test-retest reliability of isometric strength was 0.95; the variation coefficient (VC) was 19%.

Dynamic strength: The subjects performed a series of four consecutive isokinetic flexion-extension movements against the lever arm of the dynamometer that moved at a velocity of 100°/s. The knee extension was initiated at a joint angle of 90° and ended at 160°. After each extension, the leg was returned passively to the starting position from which the next contraction was immediately initiated. Maximal dynamic strength was determined as the peak torque (Nm) recorded during these series of knee extensions (ICC = 0.98, VC = 18.2%).

Speed of Movement of Knee Extension

The subjects performed four tests. They were asked to extend the lower leg at the highest possible speed from a knee-joint angle of 90° to an angle of 160°. The degree of resistance on the lever arm was individually determined as a percentage of the maximum torque that the subject could develop isometrically in the knee angle from which the knee extension was initiated (90°). The tests were performed with an external resistance of 1%, 20%, 40%, and 60% of this isometric maximum. At each test, the maximal velocity of the lever arm (°/s) was recorded to determine speed of movement (ICC = 0.96–0.91, VC = 11.2–17.8%).

Counter-Movement Jump Performance

A vertical counter-movement jump with hands positioned at the waist was used to assess the lower-limb explosive performance capacity³⁴ in movements in which a concentric (shortening) contraction follows an eccentric (stretch) muscle contraction. This type of stretch shortening of the muscle is natural and efficient in activities of daily living. This test was performed on a contact mat, recording the flight time in milliseconds. The obtained flight time (t) was further used to determine the jump height ((h) $h = gt^2/8$, where $g = 9.81 \text{ m/s}^2$). The best of three trials was recorded to determine the test score (ICC = 0.99, VC = 24.9%).

Statistical Analysis

The changes in strength, counter-movement jump, and speed of movement (dependent variables) in the WBV, RES, and control groups (independent variables) were analyzed after 12 and 24 weeks. Statistical analysis was performed using an analysis of variance (ANOVA) general linear model for repeated measures: (3 (group) × 3 (time)) for strength and counter-movement jump; (3 (group) × 3 (time) × 4 (resistance)) for speed of movement. After an

overall *F*-value was found to be significant, preplanned contrast analyses were performed to evaluate significant pre-mid and mid-post changes in each group and differences in time between groups (interaction). A Bonferroni correction was used to adjust the *P*-value in relation to the number of contrasts that were performed. Differences in pretest values between groups were assessed using a one-way ANOVA model. Test/retest reliability of all measurements was assessed using the ICC. All analyses were executed using the statistical package Statistica, version 6 (Statsoft, Inc., Tulsa, OK). Significance level was set on $P < .05$.

RESULTS

Training Experiences and Dropout

In the WBV group, subjects became acquainted with the training program rapidly. There were no reports of adverse side effects. Only during the first sessions were some erythema, edema, and itching of the legs reported after vibration exercise. These phenomena resolved rapidly after training. Most subjects enjoyed the vibration loading, but they did not consider it to be a difficult workout. They generally reported a moderate degree of muscle fatigue at the end of each session.

Sixty-nine of the 89 subjects completed the study properly. Six (WBV = 3, RES = 3) women dropped out voluntarily in the first weeks of training because they experienced an incompatibility between the test/training program and other commitments of daily living. Another six subjects (WBV = 1, RES = 1, control = 4) dropped out because of injury/health problems not related to the study protocol. Seven (WBV = 2, RES = 5) had to leave the program because of mild knee-joint discomfort. Three subjects, all participating in the RES group, dropped out because of anterior knee pain (patellofemoral dysfunction, patellar tendinopathy). It seems that these dropouts were related to the training program. Four subjects (WBV = 2, RES = 2) reported some knee pain during training because of mild degenerative changes due to a history of knee injuries. One subject (RES) did not complete the program because of back problems. All remaining subjects of the WBV group ($n = 24$) and the RES group ($n = 20$) performed 72 training sessions. The basic characteristics of the remaining 69 subjects who completed the study are given in Table 2. No significant differences in age, body mass, body mass index, or height were detected between the groups at the start of the study (Table 2).

Table 2. Subject Characteristics

Characteristic	Whole-Body Vibration ($n = 24$)	Resistance Training ($n = 20$)	Control ($n = 25$)	<i>P</i> -value*
	Mean ± Standard Error			
Age	64.6 ± 0.7	63.9 ± 0.8	64.2 ± 0.6	.787
Body mass, kg	66.5 ± 1.8	70.4 ± 3.0	68.7 ± 3.0	.515
Body mass index, kg/m ²	26.2 ± 0.8	26.9 ± 0.8	26.4 ± 1.2	.939
Height, cm	159.5 ± 1.0	161.0 ± 1.2	160.9 ± 1.3	.564

* Results of one-way analysis of variance between pre-test group means.

Maximal Strength

There were no significant differences in isometric strength and dynamic strength between groups at the pretest ($P=.881$; $P=.726$). As can be seen in Figure 1(A, B), which indicates knee-extensor torque for the three groups, isometric and dynamic strength increased from pretest to mid- and posttest in the WBV and RES groups, whereas there was no improvement in the control group. Statistical analyses confirmed these observations. Isometric strength

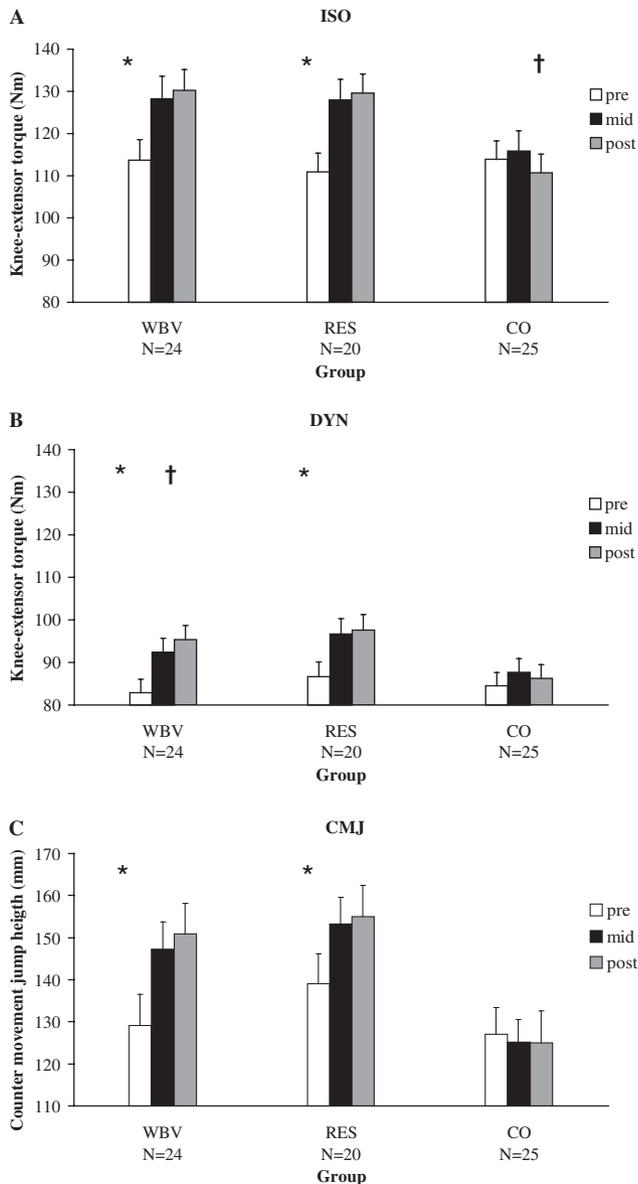


Figure 1. Mean and standard error (SE) before (pre), after 12 weeks (mid), and after 24 weeks (post) in the whole-body-vibration training group (WBV), the resistance training group (RES), and the control group (CO). A: Maximal isometric knee-extensor torque (ISO), B: Maximal dynamic knee-extensor torque (DYN), C: Counter-movement jump height (CMJ). There is a significant interaction effect (group \times time) at $P < .05$. *Mid-test values are significantly higher than pretest values at $P < .05$ (contrast analyses). †Posttest values are significantly higher than mid-test values at $P < .05$ (contrast analyses).

changed differently over time in the three groups; a significant interaction effect (group \times time) was found ($F(4) = 16.066$, $P < .001$). Contrast analyses clarified that isometric knee-extensor strength (Figure 1A) increased significantly ($P < .001$) over 12 weeks in the RES group (mean \pm standard error = $16.8 \pm 2.9\%$) as well as in the WBV group ($12.4 \pm 2.1\%$), whereas no significant increase was found in the control group ($P = .405$). The additional increase after 24 weeks of training was not significant in the RES group ($P = .336$) or the WBV group ($P = .470$). Isometric knee-extensor strength significantly decreased in the control group from mid- to posttest ($-4.3 \pm 1.6\%$; $P < .05$). No significant difference in training effect was found between the WBV and RES groups ($P = .558$), but both groups differed significantly ($P < .001$) from the control group.

Dynamic strength also changed differently over time in the three groups; a significant interaction effect ($F(4) = 7.201$, $P < .001$) was found. Contrast analyses showed a significant increase ($P < .001$) in dynamic strength (Figure 1B) in the RES group ($12.5 \pm 2.7\%$) and in the WBV group ($12.1 \pm 2.7\%$) after 12 weeks of training, whereas no significant change was found in the control group ($P = .156$). There was no additional increase after 24 weeks of training in the RES group ($P = .498$). In the WBV group, a small but significant additional increase was found ($3.7 \pm 1.7\%$; $P < .05$). Dynamic strength remained unchanged in the control group between mid- and posttest ($P = .227$). The training effect was not significantly different between the WBV and RES group ($P = .570$), whereas both groups differed significantly ($P < .004$) from the control group.

Speed of Movement of Knee-Extension

No significant differences were found between groups in knee-extension speed of movement (SM) (1%, 20%, 40%, 60%) at pretest ($P = .487$, $P = .864$, $P = .644$, $P = .343$). As can be seen in Figure 2A, B, C, representing SM of knee-extension with an external resistance of 1%, 20%, 40%, and 60% of isometric maximum, SM increased from pretest to mid- and posttest in the WBV group and RES group, whereas there was no change in the control group. The increase in SM was larger in the WBV group than the RES group, especially at low resistances (1%, 20%). The statistical analyses of SM revealed a nonsignificant group-by-time-by-resistance effect over the 12-week training period ($F(6) = 1.871$, $P = .088$). However, after 24 weeks (Figure 2) a significant group-by-time-by-resistance effect was found ($F(6) = 2.374$, $P < .040$). Contrast analyses detected a significant increase in SM1% ($P < .020$) and in SM20% ($P < .003$) only in the WBV group after 24 weeks of training ($7.4 \pm 1.8\%$ and $6.3 \pm 2.7\%$, respectively). In the RES and control groups, no significant differences between pre- and posttest were found for SM1% (RES, $P = .090$; control, $P = .184$) or SM20% (RES, $P = .067$; control, $P = .410$). The SM40% and SM60% did not change in any of the groups after 24 weeks (P -value between .141 and .992). The training effect was not significantly different between the WBV and the RES group in SM1% ($P = .391$) and SM20% ($P = .142$). There was a significant difference over time between the WBV group and the control group in

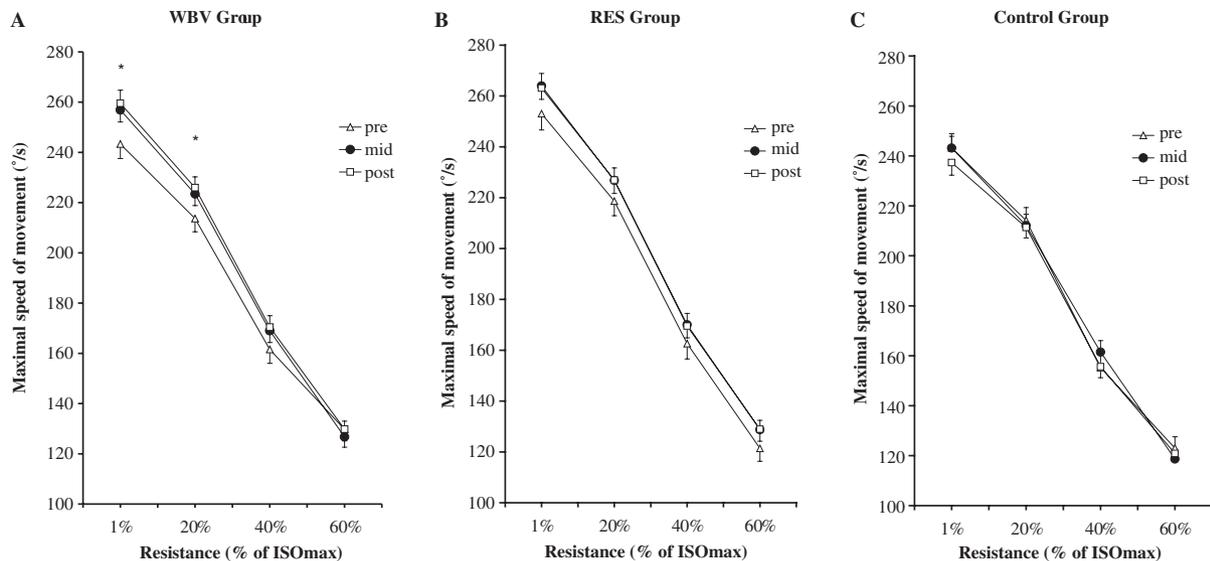


Figure 2. Speed of movement of knee extension (mean \pm standard error) with an external resistance of 1%, 20%, 40%, and 60% of the isometric maximum (ISOMax) before (pre), after 12 weeks (mid), and after 24 weeks (post). A: the whole-body-vibration training group (WBV), B: the resistance training group (RES), C: the control group. There is a significant interaction effect after 24 weeks (group \times time \times resistance) at $P < .05$. *Posttest values are significantly higher than pretest values at $P < .05$ (contrast analyses).

SM1% ($P < .040$) but not in SM20% ($P = .146$) after 24 weeks. The RES group was not significantly different from the control group in SM1% ($P = .166$) and SM20% ($P = .106$).

Counter Movement Jump Performance

There were no significant differences between groups at pretest ($P = .544$). As seen in Figure 1C, representing the counter-movement jump height for the three groups, jump height increased from pretest to mid- and posttest in the WBV and RES groups, whereas there were no changes in the control group. Statistical analyses clarified that jump performance changed differently over time in the three groups; a significant interaction effect (group \times time) ($F(4) = 12.384$, $P < .001$) was found. Contrast analyses clarified that counter-movement jump height increased significantly ($P < .001$) over 12 weeks in the RES ($12.1 \pm 2.9\%$) and in WBV ($16.0 \pm 2.8\%$) groups but remained unchanged in the control group ($P = .500$) (Figure 1C). No additional significant changes occurred after 24 weeks in any of the groups (RES, $P = .528$; WBV, $P = .155$; control, $P = .986$). No significant difference in training effect was found between the WBV and RES groups ($P = .382$), whereas both groups differed significantly ($P < .001$) from the control group.

DISCUSSION

This is the first study to investigate the long-term effects of WBV training on muscle strength in older women. The results of the study clearly demonstrated that 12 weeks of WBV training lead to a significant improvement of knee-extension isometric strength, dynamic strength, and speed of movement. Counter-movement jump performance increased significantly as well. The additional improvement after 24 weeks of training was small. Based on these results,

it can be said that WBV is a suitable and efficient strength training method for older women.

WBV training consists of two components: the vibration stimulus and the unloaded exercises performed on the platform. It cannot be denied that the unloaded exercises attribute somehow to the strength gain in older women, but the findings of a recent placebo study²⁰ indicated that, in untrained women, strength increases after WBV were clearly associated with the vibration stimulus, because an identical exercise program performed without vibration did not result in a significant strength gain. Based on the findings in this placebo study,²⁰ based on the fact that vibration resulted in increased muscle activity in young²⁰ and old (pilot study—data not shown) subjects and on findings from previous studies,^{19,22,28} it is suggested that the major part of the gain in strength is due to the muscle activity provoked by the vibration stimulus.

The magnitude of the strength gain on isometric and dynamic strength of the knee extensors after 24 weeks of training was 15.0% and 16.1%, respectively, for the WBV group and 18.4% and 13.9%, respectively, for the RES group. These data indicate that strength gain after WBV training was comparable with strength increases after an equal number of conventional resistance training sessions using weight machines. In contrast to the unloaded exercise in the WBV program, the relative training load in the RES program was individually tuned using the concept of repetition maximum. Further research is needed to determine whether, in WBV training, an individualized training load may optimize the effect on strength. In the RES group, the gain in isometric strength (18.4%) was low compared with the knee-extensor strength increases recorded in some other studies ($\pm 30\%$) using high resistance or explosive strength training programs.^{16,17,35} However, in this study, the training intensity of the RES training program was designed according to the ACSM recommendations to improve, but not to maximize, strength in older adults.³³

After an identical WBV training program of 12 weeks the mean gain in knee-extensor strength (isometric and dynamic) was 12.8% in young women²⁰ and 12.3% in older women in this study. After WBV training, a lower strength gain in older adults than in young adults could be expected because older adults might be less sensitive to the vibratory stimulus, for instance because of a decreased number of muscle spindles.³⁶ Because the older women had a higher body weight (10.0%) and a lower force generating capacity (24.7%) in isometric strength, the relative load of an identical WBV training program is higher in old than in young adults. Therefore, a comparison between WBV training effects of young and older adults is only possible if training intensity in WBV is determined individually. Nevertheless, the data from this study suggest that the muscle receptors of the older women are sensitive enough to the vibratory stimulus³⁷ and evoke muscle activity in response.²⁰

Neural and intramuscular adaptations occur in the neuromuscular system in response to resistance training.^{38,39} It has been shown that initial increases in maximal strength are large during the first months of RES training in older women,¹⁸ particularly due to neural adaptations.³⁹ As training continues over several months, strength development may take place at a diminished rate,¹⁸ and intramuscular changes become more important.³⁹ In this study, the gains in isometric and dynamic strength realized between 12 weeks and 24 weeks of training were small and mostly statistically insignificant, 2.7% and 3.7% ($P = .046$), respectively, for the WBV group and 1.7 and 1.4%, respectively, for the RES group. In both the WBV and the RES group, most of the strength gain was realized after 12 weeks of training. These findings suggest that neural adaptations are the most relevant mechanism of strength gain not only in the RES group but also in the WBV group, as was hypothesized for the young adults.²⁰ It is likely that WBV training elicits a biological adaptation that is connected to the neural potentiation effect, similar to that produced by resistance and explosive strength training. It is well known that the input of proprioceptive pathways (Ia, II, and probably Ib afferents) plays an important role in the production of force during isometric contractions.⁴⁰ During WBV, these proprioceptive pathways are strongly stimulated. The vibratory stimulus activates the sensory receptors, which results in reflexive muscle contractions. The increase in isometric strength after WBV training and thus after extensive sensory stimulation might thus be the result of a more efficient use of the positive proprioceptive feedback loop in the generation of isometric force.

Although most training effects were identical after WBV training and RES training, only the WBV group showed significant gains in SM1% and SM20% of knee extension after 24 weeks of training (7.4% and 6.3%, respectively), but the training effect was not significantly different between the WBV group and the RES group, despite a nonsignificant gain in SM1% (4.6%) and SM20% (4.7%) in the RES group ($P = .090$ and $P = .067$, respectively). So it can be concluded that WBV training was efficient in improving SM of knee extension in older women but not more efficient than RES training. The significant chronic effect of WBV training on the relative force-velocity curve of knee extension is in accordance with the hypothesis

that the tonic vibration reflex primarily affects subjects' ability to generate high firing rates in high-threshold motor units.³⁰ In addition, it is suggested that the recruitment thresholds of the motor units during WBV is lower than with voluntary contractions,³¹ probably resulting in a more rapid activation and training of high-threshold motor units.²¹ Considering the preferential loss of high-threshold fast-twitch fibers with aging,¹⁰ WBV training might increase the mean fast-twitch fiber area and positively affect speed of movement. In younger adults, no significant chronic effect of WBV training on the relative force-velocity curve of knee extension was found.²⁰

Peak muscle power is a strong physiological predictor of functional limitations and disability in older adults.^{2,5} Because power is the product of force and velocity, the variance in maximal strength (1RM) can explain about 65% to 70% of variance in knee-extensor peak power in older adults.¹⁵ The measurement of SM of knee extension pre- and posttraining in this study neutralizes the effect of maximal strength, because the resistance was determined as a percentage of the isometric maximum of each individual. The increase in SM1% and SM20% means that, at the end of the WBV training program, older women reached higher velocities in knee extension with higher resistances. Additionally, the results showed an increase in counter-movement jump after 12 weeks of WBV (16.0%) and RES training (12.1%). One study⁴¹ showed the involvement of the stretch reflex and thus involvement of the Ia afferent input in the force potentiation during a lengthening-shortening contraction in the counter-movement jump. The stimulation of the sensory receptors and the afferent pathways with WBV might, therefore, lead to a more efficient use of the stretch reflex in the counter-movement jump. It is suggested that the tonic vibration reflex induced a reflex sensitization of the muscle spindles and a facilitation of the reflex action on the motoneuron pool.³¹ The results of the study with young adults supported this hypothesis, because the WBV group significantly improved (7.6%) in counter-movement jump performance after 12 weeks of training, whereas the RES group, with lower sensory stimulation, did not.²⁰ In this study with older women, the WBV and RES groups increased significantly (16.0% and 12.1%), with a slightly larger gain in the WBV group but no significant difference in training effect between the two groups. However, the real contribution of the stretch reflex in counter-movement jump performance in older adults is not clear. Some studies suggested that the mechanical performance enhancement after pre-stretching is somewhat diminished with aging,⁴² whereas others have shown no age-related differences in performance with stretch-shortening-contraction.⁴³ A less explosive execution of the counter-movement jump due to fear of landing in older than in young adults may impair the role of the stretch-reflex in counter-movement jump performance of older adults. The gain in knee-extensor strength may largely contribute to the gain in counter-movement jump performance.

WBV training in older women is a safe, suitable, and efficient strength-training method. The findings of this study indicate that WBV training has great potential for application in the geriatric and therapeutic sectors as a safe, low-impact strength-training method with a low starting

threshold for those who are not attracted to or able to perform conventional resistance training. WBV training minimizes the need for conscious exertion and stress on the musculoskeletal, respiratory, and cardiovascular systems.²¹ Subjects experienced the vibration sessions as muscle fatiguing but not as vigorous training sessions. Further research is needed to investigate the influence of WBV training on functional strength and prevention of falls in older adults.

In conclusion, muscle strength and speed of movement of knee extensors and counter-movement jump performance increased significantly in older women after 24 weeks of WBV training. The magnitude of these benefits of WBV was similar to the changes recorded after a conventional RES training program considered to be a standard method of increasing strength in older adults. It is suggested that the gain in muscle performance after WBV training in older women is mainly due to the vibration stimulus. As previously shown in young women,²⁰ the effect on muscle strength of the exercises performed on the platform without vibration is limited.

ACKNOWLEDGMENTS

The authors thank Guus van der Meer, Jelte Tempelaars, and Nick De Poot for designing the WBV training program and for placing the WBV platform at our disposal (Power Plate). The authors also thank Els Van den Eede and Karel Pardaens for the medical screening of the subjects. The cooperation of the subjects is greatly appreciated.

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